

A Design Language for Expressing Structural Concepts

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Abstract: this paper presents a design language developed for expressing structural concepts during design workshops in the early phase of the architectural design process. The language operates as a design and communication tool between structural engineer and architect, by expressing the engineer's design aims of his structural proposition, through the load path(s) and the structural function(s) of the elements. It filters the large amount of structural information in function of the architectural design paradigm by focussing on the implication of the design concept on the structural form.

The language enables to load the three-dimensional architectural model with a structural concept through the use of a limited amount of basic symbols that are easy and quick to draw, and intuitively understandable.

This language has been tested with (interior) architecture students. They show that the language is easy to learn, easy to use and that it is helpful for some students to design structures.

The presented research is part of the doctoral work of the author on the communication and collaboration of architect and structural engineer, early in the design process. In this action research, the author uses more than fifteen years of his own experience in structural education and engineering practice.

1. Problem definition

The architectural design is experienced through the overall shape and materiality of its surfaces. This is the outer, experiential part of the design. The shape orders the architectural space and needs to be supported by the structure.

Several types of relationships between structure and architecture have been defined by Macdonald (1997): structure ignored, structure accepted, structure symbolised and true structural high tech. They vary between structure that has no implication on the architectural shape, to structure that not only determines the architectural shape, but also the nature of the adopted architectural vocabulary.

It is the author's experience as a professional structural engineer, and as a structural teacher to architecture students, that many structures are designed after the architectural design has been shaped, with little to no influence of the structural design on the architectural design decisions. In these cases the structure at its best blends in the architectural shape, but is often standing in the way of the architect's wish for a certain architectural expression. In his doctoral research, the author tries to find a way to let the structural design inspire and guide the architectural design process, instead of blocking it.

According to Macdonald (1997), a structural design process can be subdivided in to two parts. First, there is a preliminary design stage, when shape and general arrangement of the structure are devised. In the second stage, the structural calculations are performed and the dimensions of the various structural elements are determined.

This first preliminary design stage can be considered as a ‘wicked problem’, as Rittel and Webber (1973) have called it. Here a found solution is never the best solution, merely better than a previous one, and a design problem only becomes clear when a solution is found. In this design stage, the outcome can be considered a structural concept, where shape and general arrangement of the structural elements (and their interconnections) are decided, but not the materiality and dimensions of these elements. This structural concept thus delineates the general shape of the structure, and is the outcome of a design process that contains several possible solutions. (This general shape is not one fixed model¹, but groups a range of models).

The same can be stated about the conceptual design of the architect: it delineates the general shape of the architecture, and it is only one of the several possible design solutions.

Therefore if we want architect and structural engineer to design together the shape of the building, it is important that they collaborate when architectural concept and structural concept are formed, and a solution is found that brings both concepts in congruence. This means that they work together in the early stages of the design process, when the design is still in its conceptual phase.

Both architectural and structural design are dependent on each other, and therefore unable to find a final design solution without input from the other disciplinary design. Lewis and Mistree (1997) have proposed to use game theory to reframe this multi-disciplinary design process and introduce the concept of non-local variable as the information one disciplinary design needs from the other to be able to ‘optimize’ its own design.

This raises the question of which information exchange is required during this collaboration of architect and structural engineer? It is the author’s view that during the conceptual design negotiation, this information should contain the discipline related design model together with the design aims of the conceptual design proposition (i.e. of the architect or of the structural engineer) (Luyten, 2010). The presented design model delineates the shape, and the design aims express the logic to change this fixed three-dimensional model within the conceptual design proposition. As such the information exchange is not just a fixed design model (and thus one shape), but a range of models (and shapes) that are contained within the proposed design concept of the architect or of the structural engineer. And thus in order to understand these discipline related design propositions, architect and engineer need to possess sufficient knowledge on the opposite discipline. Part of the author’s research is an investigation in the essence of this required knowledge on the opposite discipline.

¹ Model in this context is used as a precise determined three dimensional shape of a design

The design negotiation between architect and structural engineer operates on the level of the shape of the conceptual design proposition. The shape links both design processes: for the architect the shape relates to the architectural expression and the organisation of space, and for the engineer to the structural logic of the load distribution.

2. Structural concept

A structural concept groups several particular structural solutions by removing their uncommon characteristics and retaining the characteristics that are similar to all of the solutions. As stated above a structural concept delineates the shape and the general arrangement of the structural solution. In the author's view, it pertains the paths the different loads follow through the elements from their starting point to the supports of the structural concept. This characteristic is called the flow of forces (Engel, 2009) or the load path (Millais, 2005).

Another characteristic of the structural concept is that it contains the structural function of each of its elements. This structural function is defined by Engel (Engel, 2009) as: load reception, load transfer and load discharge. It describes what is required of each structural element in order to bring the load to the supports of the structure. To perform this function each element will have to withstand particular internal forces. (In the second stage of the structural design process, these elements will then be dimensioned to withstand these internal forces).

2.1. Structural design aims

In the author's view, these load paths and the structural function of the different elements, express the essence of the structural logic of a conceptual design, and thus lay at the heart of a conceptual design proposition. When the structural engineer proposes to the architect a structural concept during the design negotiation, one can state that the load paths and the structural function of the elements are design aims the engineer has set in his proposition: it is his chosen structural logic of how the loads will be transferred through the structure. These design aims lay at the basis of the proposed structural concept and thus delineate the structural shape.

Architect and structural engineer designing together, involves a negotiation process of the organisation of space and shape. And thus when the architect wants to grasp the range of possible shapes a structural concept contains, it is important he understands the load paths and structural functions of the engineer's proposition. In the language developed by the author, these design aims (i.e. load paths and structural functions) are clearly expressed.

The configuration and order of the structural elements are regulated by the load paths. As such the structural shape is delineated to some degree by these load paths. (These load paths need to be considered for vertical as well as for horizontal loads, as part of its stability validity).

The material form of the structural elements is related to their function: if a structural element is required to perform a function, it needs to withstand the consequential internal forces through its material dimensions. Changing its material form will affect the structural function it can perform (Engel, 2009). In engineering sciences, the structural function of an element is most commonly expressed by the concept of internal forces, although these internal forces are basically the consequence of a required function, and not the function itself as Engel has described it.

2.2. Structural function

If we consider this structural function within systems thinking, we can describe the ‘load reception’ as input, ‘load transfer’ as an internal operating process, and ‘load discharge’ as output². Presenting this structural function through system thinking is rather unusual within structural engineering sciences, but it brings forward the distinction between function and the consequences of this function, which are the internal forces and even the required material form.

We can for example define the function of ‘transmission’ when the element transfers the load force from one end to its other end, and the force input and output remain on the same axis (see figure 1). This axis lays then in the centre of the element. This function leads to normal forces in the element.

There is a distinction to be made when this function induces tension or compression in the element, because of the impact on the material form. In the latter case, buckling is at stake and can lead to wider sections. A structural typology with this function under tension is a tie, and with this function under compression, a rod.

Another example of structural function can be defined as ‘relocation’, when the force input is relocated from its axis to a parallel axis (i.e. of the force output) and the plane defined by both axes coincide with the centre of the structural element (see figure 1). (It should be noted that secondary forces are required -as output or input- for this system to be structurally in balance). This function leads to shear forces and bending moments in the element. A structural typology with this function is a cantilever beam.

One structural element can have several structural functions, but during the design negotiation between architect and structural engineer, not all of them need to be made explicit. The information exchange between architect and engineer is focused on the shape of the design proposition. This means that that part of the functions that are not decisive for the dimensioning of the material form can be filtered out, in order to prevent excessive information flow.

In its most abstract understanding, a structural element in a conceptual design does not represent per se a specific structural typology (e.g. beam, column, tie, slab). It merely symbolises a visual shape (e.g. a line symbolises an object with

² In this model of system thinking, every load force can be switched from ‘input’ to ‘output’ (and vice versa) as long as the direction of the force is inversed. When all the load forces on the model are switched to ‘input’, the result shows all the forces working on an element in structural balance.

a linear visual characteristic: this can be a prismatic beam, or a lattice girder or even a vierendeel girder). This makes it possible to express a design proposition of a structural concept through the basic elements of an architectural model. This means that during design negotiation, the architectural model can be used as a starting point for the structural concept where the (architectural) elements are loaded with load path(s) and structural function.

3. Design Language

The language that is presented in this paper, is developed to be used during workshops where architect and structural engineer are designing together. It expresses the structural logic of the engineer's conceptual design proposal through load paths and structural function of the conceptual elements. It is a three dimensional language that is quick and easy to draw, with symbols that are intuitively understandable. Because part of the strength of a collaboration workshop lays in the quick response and feedback on co-designer's input, it is important that this language can be quickly and easily used with only pencil and paper.

This language also has its use in pure structural design and education, because of its quality to bring forward the essence of a structural concept through the simplicity of its application.

With this language a designer can easily produce proposition drawings as Lawson (2004) calls it, in order to have 'a conversation with the drawing' (Schon, 1984). The language helps the designer to put down on paper his ideas on a structural concept he has developed to that stage, in order to take distance, rethink it and possibly redesign it. It allows to quickly put down different scenarios of conceptual design solutions, to be evaluated by the structural engineer or by the architect within a collaboration workshop.

This language can be used for loading the architectural elements of the design propositions the architect makes, with structural information: the architectural model gets loaded with symbols expressing the load paths and structural functions of its different elements. This information will guide the architectural design process in congruence with the structural design.

The author has developed and successfully tested this language during workshops in his own engineering practice, and during design studios of the architecture education through action research.

3.1. Load path

In this chapter the architectural element that is chosen as example to explain this language is a flat plane. This can represent a wall or floor or any architectural shape that can be represented by a flat plane.

To express the direction of the flow of forces, the main structural axis of an element is expressed by a line with the symbol ● at the side of the element, where the force is discharged (see figure 2). The connection with the other

elements then, makes clear which element will then receive the load. (It is even possible to use the size of symbol ● to express the relative amount of the load distribution). In this manner the path of the load can be traced throughout the different elements.

3.2. Structural function

As described above, the structural function of an element is related to the material form of the element. Therefore, a distinction is made in the language between the above described ‘transmission’ function in tension, and in compression (when buckling is at stake and requires the material form to be wider in the middle). Or one could say that there is a different symbol for a structural element that needs to withstand a positive normal force, then when it has to withstand a negative normal force. The symbol used for compression is two arrows pointing at each other ($><$), and for tension, two arrows pointing away from each other ($<>$) (see figure 3).

Another structural function as mentioned above, is ‘relocation’, where a load force from one side of the element gets transferred to the other side. The symbol used here is **I**, starting on the structural axis pointing towards the zone in the element that is under tension due to the bending moment (in figure 4 it is the upper side of the element). A distinction is made between tension in the upper side (**I** on top of the axis) and the lower side (**I** under the axis), because of the relation with the material form: the tension part of the element has no buckling problems and can be made slender compared to the compression part. The **I** is placed on the axis where the bending moment is the highest and the material form requires the biggest height. At this side of the element, secondary forces will occur as mentioned in chapter 3, to keep the element in structural balance. The symbol **I** together with the axis, can be seen as a suggestion of the bending moment diagram, or of an optimised prismatic beam, or even of a structural system working under compression and tension (see figure 4).

We can define another structural function as dividing a central loaded force to both ends of the structural element. This is in fact a combination of two elements with the structural function ‘relocation’, where each part of the load force is transferred to one side of the element (see figure 5). A structural typology with this function ‘division’ is a simple supported beam. To be able to perform this function, the material form needs height in the middle of its length, where tension will occur in the lower side of its section and compression in the upper side, when the **I** is placed underneath the axis.

3.3. Advanced applications

A structural element can have several functions. The function of ‘division’ and ‘relocation’ can for example be combined as shown in figure 6. In this case a part of the load is relocated to the left –and is responsible for the secondary forces-, while the remaining load is divided over both ends. The **I** is placed where the material form will need the biggest heights. The position of the **I** according to the axis, indicates on which side tension will occur due to

bending. Different combinations can be made in this manner, where even the position of the **I** can be used to indicate where on the axis the biggest height is needed. The relative size of the different **I** can even express the relative heights of the material form along its axis.

These functions, that are related to bending of a structural element, can be required in any relative direction of such an element. In this three-dimensional language, this is expressed by orienting the **I** in the appropriate direction, as shown in figure 7. The left element can be seen as a horizontal beam, dividing the horizontal load (through bending), to both its sides. It will require a material form with horizontal 'height'. The right element can be seen as a plate, dividing the vertical load to both sides. Here vertical height will be required of the material form.

The only other symbol the language contains, is a symbol expressing the function where the structural element has to withstand torsion. This function transfers a load moment along its axis, that coincides with the axis of the structural element.

For each load (e.g. horizontal and vertical) a different colour for the symbols can be used to express the structural behaviour. This makes it possible to present different structural stories on one model alone (see figure 8).

Eventually, each element needs to be further refined in the design process, based upon the different functions the element has to perform for the different load cases. As stated above, only these functions need to be taken into consideration that are decisive for the material form, while the redundant functions can be filtered out.

Therefore, the language focuses on the implication of the structural function on the material form of the element. This material form is of course essential in the structural design, but it is also the way the structure is perceived. This perception of form is a part of the architectural design experience and as such a direct link between architectural and structural design.

In this process of refining the structural elements, the element starts out as a conceptual element not pertaining to a specific structural typology. As the refinement evolves, a specific typology will get chosen, and finally the material with the dimensions of the sections (see figure 9). An important aspect of this language is to postpone the decision of choosing a specific typology, which often imposes a specific –not always by the architect wanted- expression to the design, and narrows down too early the range of possible design solutions before other design aspects can be considered.

3.4. A collaboration tool

When architect and structural engineer are looking for creative solutions –opposed to routine solutions- while designing the shape together, they are negotiating for a design solution that brings architectural and structural concept together. This requires for the design aims of the different concepts to be in congruence (and not in opposition). A first step in this negotiation process is to express the design aims of a proposition the architect or structural engineer makes. The language presented here, brings forward the design aims of load

paths and structural functions, that the structural engineer has chosen for his structural proposition. Together with the structural model, these design aims express how the engineer wants to organize space and form in his structural concept.

The language allows the engineer to express his design in a personal way: the size of the symbols can be used to express importance, redundant functions can be left out according to the engineer's judgement, even the structural functions can be expressed through different combinations of symbols according to the chosen points of interest. Compared to the current language at hand in engineering sciences (e.g. internal forces diagrams, structural wire models) this language filters information in function of the collaboration process with the architect, and enables the engineer to bring forward design aims he has put into his concept that matter to the architectural design. It makes this language a powerful tool in this collaboration process.

4. Testing

During a collaboration workshop, the presented language is used as a design and communication tool between architect and structural engineer. This requires for the architect to be able to understand this language the engineer uses, and even to be able to actively use the language on his own. Therefore a test has been setup in order to verify if the language could be easily taught to interior architecture students, if it was a valid language for them to express structural concepts, and even if it could help them to creatively design structural concepts with it. The test was conducted in a structural seminar with 71 students. These students were in the third bachelor year of their interior architecture education. Prior to the test, they had followed their structure courses in the first and second year, which gave them a very basic education on structural understanding.

The students were asked in groups of two, to choose an object that expressed the meaning of 'shelter'. They were guided by the author, in structurally analysing their chosen object. After these moments of consultation, the students made a presentation that expressed their structural understanding of the object. They were told to make this presentation for their fellow students as audience, in the language they preferred.

After they handed in this presentation, the new language presented in this paper, was taught to them in a time span of one hour and a half: after an introduction in the language, some small exercises of applying the language were made with the whole class. Then they were asked to make the same presentation as the one they had handed in, but now with the obligation to explain the structural behaviour of their object with the new taught language (see figure 10). A questionnaire was filled in by the students after handing in this last assignments, in order to poll their opinion about this new language. (59 students filled in the questionnaire).

After this assignment, the students were asked to make design variations on the structural concept they had established of their object. For each variation a

structural concept had to be developed. It was required for the students to develop this concept before a new variation was designed. They were free to use the new language or not during this design process. After handing in these design variations, they were again questioned about their opinion on this language in this design exercise. (53 students filled in the questionnaire).

These are the main results of both questionnaires:

1. The language is **easy to learn**:
 - Learning the language is perceived as being (very) easy. The symbols are not confusing and are linked to an intuitive understanding of what they mean. Only a few students found it difficult to learn the language.
2. The language is **easy to use**:
 - Most student (86%) are confident to be able to explain the behaviour of a structure, that they understand, with the new learned language.
 - 90% of the students find that the essence –in their view- of the structural behaviour could well be explained with the new language.
 - With this language, the students find it clear how to follow the structural load path.
 - With this language, the students find it clear what the internal forces are in the structural elements.
 - About half of the students first draw the symbol ● (load path) for the whole structure and afterwards the functions, the other half do not follow this procedure. About the same students follow the same procedure of going through the load path and afterwards looking at the functions when trying to understand a structure.
3. **Advantages** of using the language:
 - About half of the students feel that their general structural knowledge is increased by the use of this language (the other half do not experience an increase).
 - Most students (81%) feel they can tell more about the structure in one image with the new symbols, then with their usual language. With the new symbols they need less images to explain the structure.
 - Most students (75%) find that explaining a structure with the new language is more comprehensible than with the classical internal forces diagrams.
 - In case other people would understand these symbols, 75% of the students would prefer using these symbols above the classical internal forces diagrams to explain a structure.
4. The language **helps to design structural concept**:
 - Most student (85%) find it an asset to be able to use this language for this variation design exercise.

- 85% of the students find it positive for their design process not to have to conceive the structure of their design into details, and to be able to work only with a more abstract conceptual structure.
- About 70% of the students use the language during their design process in this exercise.
- 40% of the students that use the language during their design process, get at some point new structural design ideas through the use of this language.
- More than 70% of the students prefer to apply the same kind of design methodology of focussing on the structural behaviour in the future, in order to find creative design solutions.

In order not to influence the results of this test, no feedback was given to the students on their use of the language in the exercise they made. With feedback students will probably improve their understanding of this language.

The questionnaires also reveals that only 25% of the students consistently analyse the structure of their design variation before proceeding to the next design variation. A higher percentage might have convinced more students the advantages of using the language during the design process.

5. Conclusions

The presented language has been developed as a design tool for workshops where architect and structural engineer design the shape together. It enables to express the range of possible structural solutions a proposition for a structural concept contains. This is done by articulating the load path(s) and structural functions of the elements on the structural model. The language presents the structural behaviour of a design proposition through its implications on the material form. This form is a direct link between structural design and architectural expression.

The concept behind this language is to organise structural knowledge for designing shape: starting from conceptual elements with a structural function, to refining these elements over structural typologies to actual structural form.

Tests with interior architecture students –with a minimum of structural education-, have shown that this language is easy to learn, easy to use and that it is helpful for some students to design structures. Although not thoroughly tested, it has already shown to be useful during design workshops of the author as engineer with architects and architecture students.

The tests also show that not all student experience benefit from the language. This can be due to the type of student, or to the lack of delivered feedback when teaching the language or to some other reason. Further research is required for a better understanding.

Although research has already shown the advantages of the language, further research is needed to refine the used symbols and to investigate its use in a professional environment.

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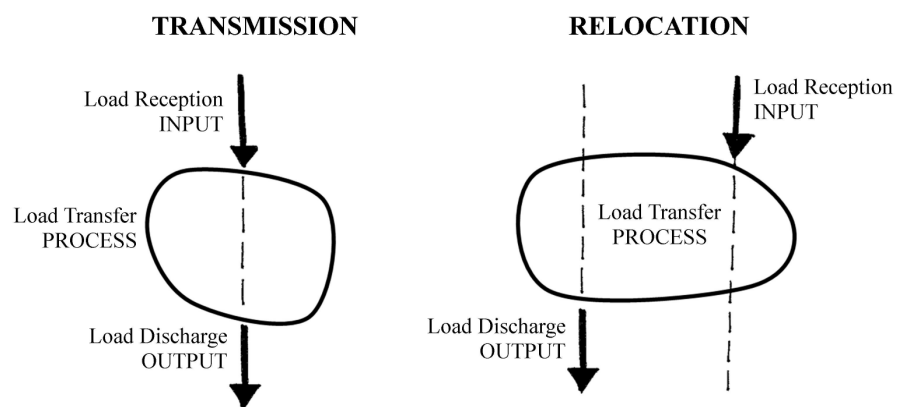
Figure 1 *Structural Function as System*

Figure 2 *Symbol for Load Path*

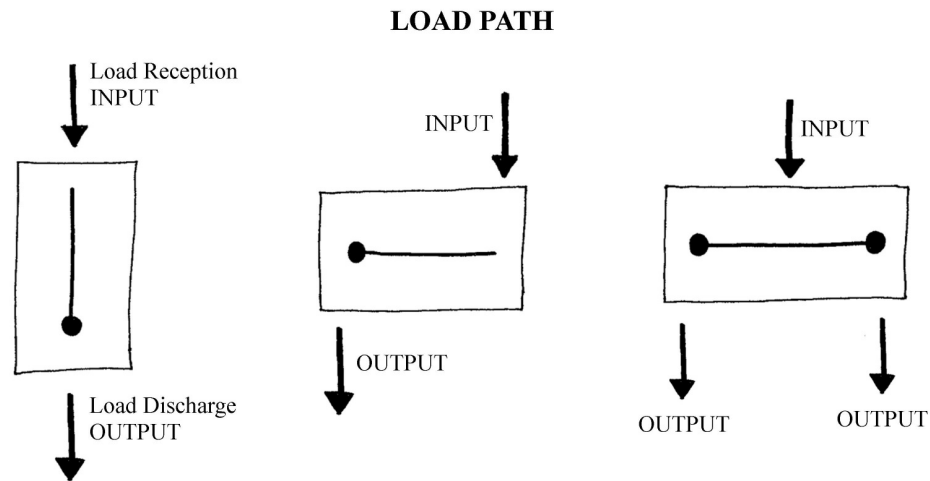


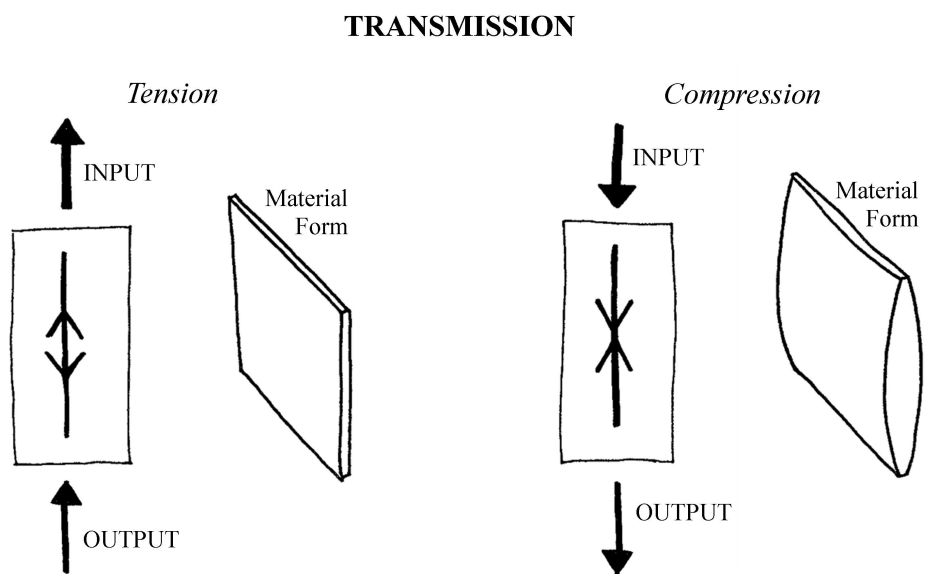
Figure 3 *Symbol for Transmission*

Figure 4 *Symbol for Relocation*

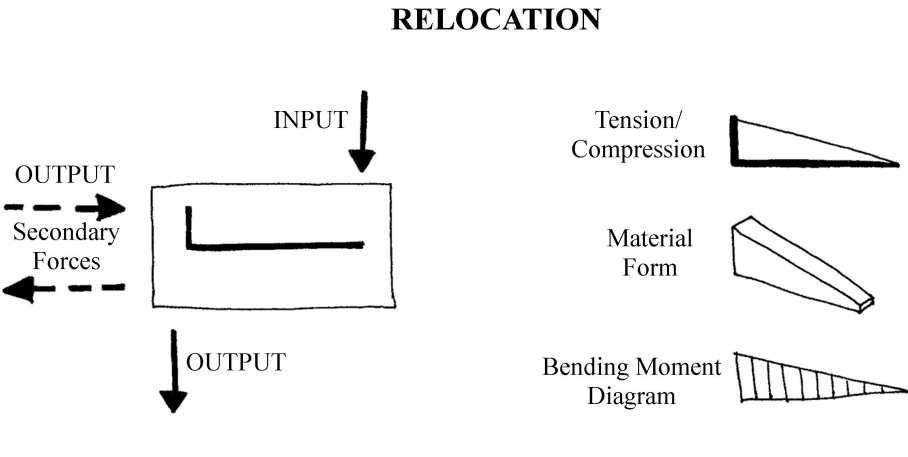


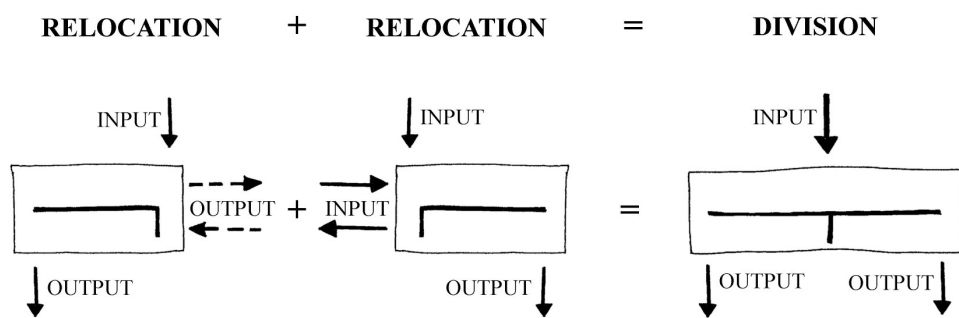
Figure 5 *Division as Sum of Two Relocations*

Figure 6 *A Combination of Functions*
RELOCATION + DIVISION

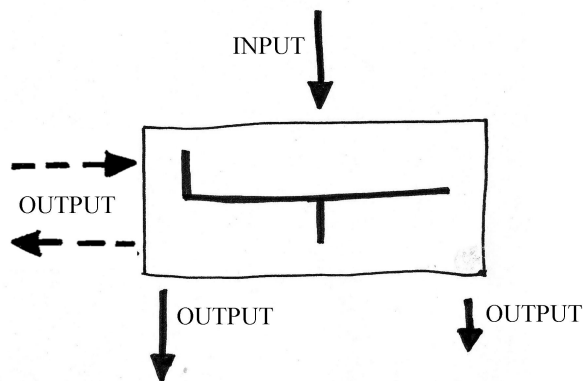


Figure 7 *Structural Function in Different Directions*

DIVISION IN DIFFERENT DIRECTIONS

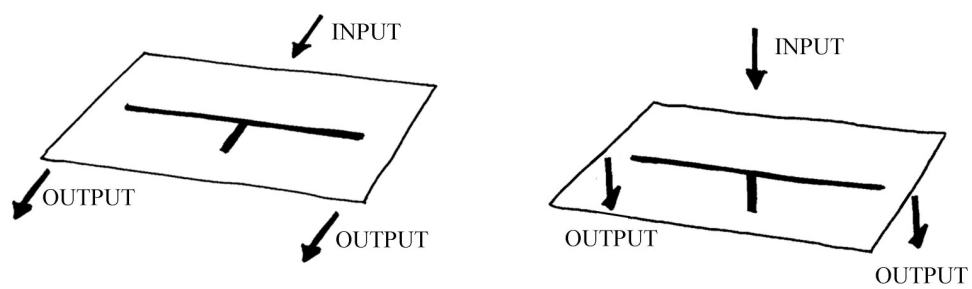


Figure 8 *Example of Different Colour Codes*

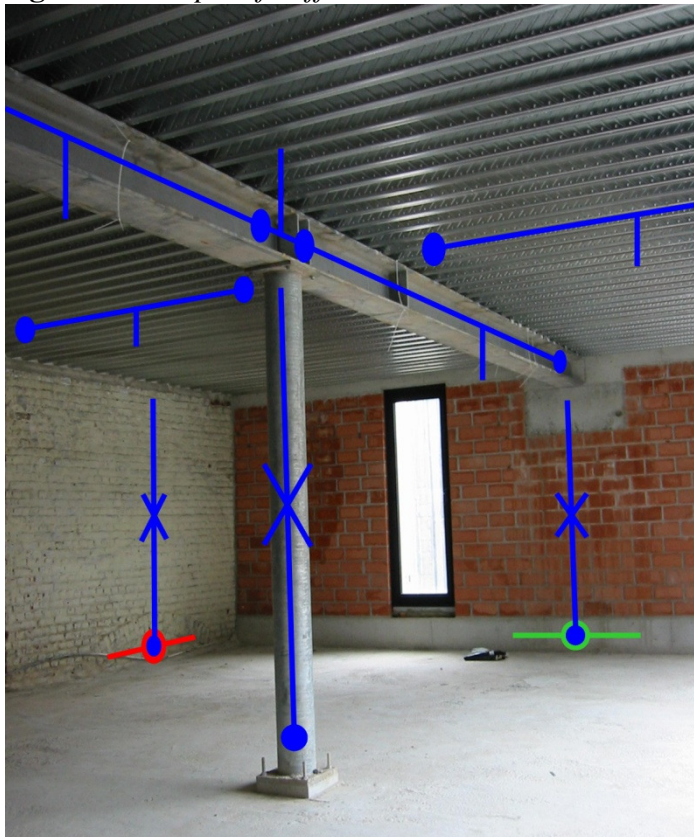


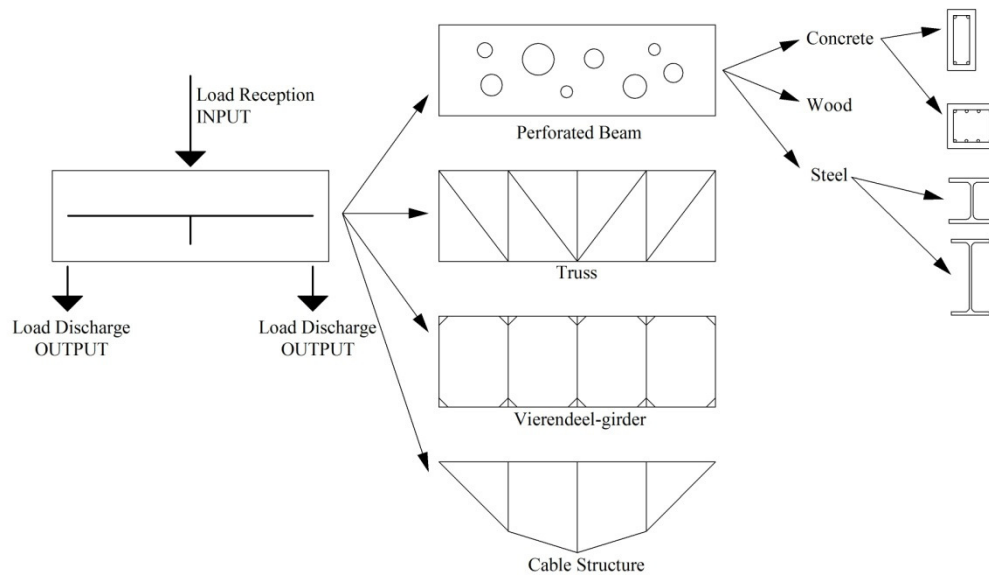
Figure 9 *Element Refinement*

Figure 10 *Example of New Language Applied by Student*

